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Geothermal Well Drilling Fluid Technology

A Literature Survey

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOTHERMAL WELL DRILLING FLUID TECHNOLOGY

A Literature Survey

by

K. J. Liles,[1] Leon Y. Sadler III,[2] and Alan H. Goode[3]

ABSTRACT

This Bureau of Mines paper describes the composition and properties of drilling fluids for use in high-temperature geothermal wells, and summarizes the problems encountered with fluid use at the known major geothermal sites throughout the world. These include the western continental United States, Hawaii, Italy, Iceland, Japan, New Zealand, and Turkey.

Water-base drilling fluids of 9- to 10-lb/gal weights are relied on primarily for geothermal well use, although air drilling is sometimes used. Bentonite-lignite-water systems have been used most often, and additives such as polyacrylates, lignosulfonates, and chromates are employed to improve the properties of the basic system.

INTRODUCTION

Geothermal energy, the energy derived from the Earth's magmatic heat, is a relatively untapped resource. Power obtained from geothermal energy is comparable in cost to that produced by fossil fuels, and using it circumvents many environmental problems (8)[4] such as land restoration following strip mining or disposal of radioactive wastes. Specific geographic and economic conditions dictate the development of geothermal energy sources. The source should be near the consumer, and the energy produced cannot be in competition with other energy of lower cost (22).

Geothermal energy has been utilized in many parts of the world, most notably in the Western United States, Italy, New Zealand, Iceland, and Turkey. Presently, annual world geothermal power production is approximately 1,000 megawatts. Of this amount, approximately 500 megawatts is produced at The Geysers, California (22).

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[1] Research chemist.
[2] Chemical engineer.
[3] Minerals engineer.
[4] Underlined numbers in parentheses refer to items in the bibliography at the end of this report.

The drilling of a geothermal production well involves special problems. These problems, which are generally associated with a geothermal environment, typically include formations of soft or fragmented rock, high temperatures, and rapidly moving corrosive fluids. Production wells are now drilled more or less routinely in existing steam and hot water fields even though drilling is often more difficult, expensive, and dangerous than for an oil well of equal depth. More often than not, the final hole depth is decided by an equipment failure rather than by a development plant (29).

Since the temperatures encountered in drilling a geothermal reservoir often exceed 260° C, the ability of conventional drilling fluids to withstand such conditions, especially where high salinities are encountered, is questionable. This Bureau of Mines paper presents the results of an extensive literature survey covering published descriptions of the use of continuous-phase drilling fluids for geothermal wells. The report is organized according to geographic locations of geothermal areas in the following sequence: (1) Domestic areas involving the Western United States and Hawaii, and (2) foreign areas, specifically Italy, New Zealand, Japan, Iceland, and Turkey.

DOMESTIC GEOTHERMAL ENERGY AREAS

The Geysers, California

Description (8, 12, 17)

The Geysers thermal area is approximately 80 miles north of San Francisco in the Mayacmas Mountains of northern Sonoma County at the western end of a northwest-trending graben. The area is underlain by Jurassic-Cretaceous basalt, graywacke, shale, and serpentine rocks of the Franciscan Group. The thermal areas are located on the fissures closest to the serpentine body. Faulted and shattered rock is encountered near the surface. Steam-producing formations consist of medium- to fine-grained sandstones with minor thin, dark shale members, cherts, greenstones altered from basalt, and serpentine. Most of the hot springs in the area have temperatures of 50° to 100° C, pH of 2 to 3, and chloride contents of 2 ppm.

Field Development (8, 14)

The Geysers geothermal field produces dry, superheated steam. The actual drill sites are usually small owing to the rugged, mountainous terrain. Occasional blasting is required to level the location because of the sloughing effect of the soil during the rainy seasons. Big Sulfur Creek is the main water source for drilling operations, although some operators use natural spring water. Occasionally water is hauled to the more remote locations.

The California Division of Oil and Gas specifies that the wells drilled at The Geysers must be set with 20-inch conductor casing between the 100- and the 200-foot depth as protection against washout at the surface. From the conductor casing, 17-1/2-inch holes are drilled and 13-3/8-inch surface casing is set at depths ranging from 1,000 to 2,500 feet. The purpose of this casing is to shut off numerous water flows and to provide hole protection from the

unstable serpentine and fractured graywacke. A 12-1/4-inch hole is then drilled and a 9-5/8-inch liner is set to a point immediately above the steam zone to shut off deep water flows. An 8-3/4-inch hole is then drilled to total depth. The production zone is completed as an "open hole" and remains uncased.

Drilling Fluid Technology (8, 12)

The drilling fluid used at The Geysers is a low-solids gel in fresh water with lignin additives. Mechanical treatment of the system is necessary to counteract increased viscosity and maintain a usable fluid. Large, high-speed shale shakers, a desander, and desilters are used to mechanically remove the solids that cause increased viscosity. Pits require frequent cleaning to maintain a low-solids system.

Unless large water flows are encountered, air is the preferred drilling fluid because it offers increased drilling rates at the relatively low temperatures encountered and negligible effects from lost-circulation zones. If lost circulation (drilling fluid that enters the formation in large quantities and is trapped therein) is encountered when drilling a producing formation, large quantities of drilling fluid can be transmitted into the producing zone. The water is subsequently flashed from the fluid, and the remaining clay particles severely impair the porosity and permeability of the zone.

Cooling towers are not normally used at The Geysers, even though 260° C bottom hole temperatures are encountered. However, since the circulating temperature of the drilling fluid often approaches 95° C at the surface, large fans are used to blow across the shale shakers. This normally cools the mud 10° to 15° C.

Highly fractured zones create a serious lost-circulation problem. Inexpensive cottonseed hulls (approximately 12 pounds per barrel) are the common lost-circulation additive. In most cases this material is sufficient to plug the fractured zone. If the zone is extensive, however, it is sometimes necessary to cement the area before drilling is continued.

Problems Encountered (8)

A combination of air drilling and steam influx from the borehole causes significant abrasion on the drill string. Depending on steam production, it is not uncommon for return velocities in the annulus to range from 6,000 to 10,000 ft/min. Often, over 50 percent of the drill pipe is so severely eroded that the drill string is treated as an expendable item. Increased viscosity due to fluid dehydration from exposure to high temperatures as the hole becomes deeper is also a problem.

The rubber components in the blowout preventer are vulnerable to the high temperatures. The rubber softens and expands while in contact with steam and then becomes hard and brittle on cooling.

Imperial Valley, California

Description (8, 13)

The Imperial Valley is basically a flat, alluvium-filled basin with a northwest trend that extends from the Gulf of California northward to the Coachella Valley. In this area there are three major fault systems, all with northwesterly trends. The San Andreas zone is located along the northeast side of the Coachella Valley, while the San Jacinto and Elsinor fault zones are located on the northwest side of the Imperial Valley.

Field Development (8)

The Imperial Valley geothermal reservoir produces hot brine. Many geothermal wells are being drilled in the area, and there are numerous proposals for additional wells.

The geothermal wells in the Imperial Valley range in depth from 2,600 to approximately 8,000 feet. A small pilot hole is normally drilled to determine if the well has the potential to be a producer. If the well shows potential, the pilot hole is enlarged. Drilling rates range from 50 to 70 ft/hr depending on the rock structure. The drilling weights and speed are not significantly critical because of the relative softness of the rock. The thermal gradient is about 7° C per 100 feet. The hot subterranean waters have pH values ranging from 5.7 to 7.6. The total dissolved solids range from 180,000 to 340,000 ppm. A typical chemical analysis of a high-salinity brine in parts per million follows: Na--30,000 to 40,000; Ca--15,000 to 25,000; K--8,000 to 11,000; Cl--92,000 to 128,000; SiO_2--150 to 1,200.

Drilling Fluid Technology (1, 8, 18-19, 25, 27, 31)

The drilling fluid most commonly used in the Imperial Valley is a fresh water gel-lignite fluid. A simple gel fluid is used to "start" the well; when increased temperatures cause gelation and/or high water loss in the fluid system, the fluid is changed to a sodium surfactant fluid. Lignite is used in the fluid as a thinning agent to counteract the detrimental effects of high temperature. The lignite chemically prevents the clay particles from flocculating. The fluid normally has a density of 75 lb/ft^3 with a funnel viscosity of 35 to 40 seconds. The solids content is kept to a minimum to aid the drillability and to reduce the heat-carrying capacity of the fluid. As there are no high-pressure zones, the fluid weight is maintained for hole stability. Lost-circulation zones are sometimes present, but they do not cause serious problems; in most cases the formation apparently collapses near the borehole after a few hours, thus sealing itself. In a few cases it has been necessary to force cement into lost-circulation zones for control purposes. These zones may occur anywhere from the surface to total depth.

The most critical factor in any fluid circulating system is the high temperature of the circulating media. Most of the producing wells in the Imperial Valley have bottom-hole temperatures around 260° C with fluid

circulating temperatures of 95° C. On some of the extremely hot wells a cooling tower is used to reduce the temperatures. The cooling towers lower the circulating temperature about 17° to 22° C, which is enough to keep the fluid in a usable state.

Table 1 shows the materials used for making the fluid for a typical geothermal well, O'Neill, Hilliard and Ashman's Sportsman No. 1 drilled in 1961. The properties of the drilling fluid near total depth and with a flow-line temperature of 84° C are shown in table 2.

TABLE 1. - Materials used to drill Sportsman No. 1, Imperial Valley, California

Material	Drilling from surface to 2,690 ft, lb	Conversion to sodium surfactant mud, lb	Materials added to make up lost circulation, lb	Drilling from 2,690 ft to total depth, lb
Wyoming bentonite.....	12,800	-	9,800	-
Barium sulfate........	16,300	9,000	-	13,750
Treated lignite.......	9,750	19,900	7,500	-
Caustic soda..........	1,700	1,700	700	2,500
Salt..................	-	400	900	1,700
Surfactant............	-	4,600	460	4,600
Soda ash..............	-	2,400	400	1,900
Plastic foil..........	-	-	1,050	650
Fine walnut hulls.....	-	-	3,000	2,750
Fine mica.............	-	-	1,750	4,250
Cane fiber............	-	-	-	2,200

TABLE 2. - Fluid properties of Sportsman No. 1 near total depth and 84° C temperature

Weight........................lb/gal..	10.3
Viscosity...............sec/qt funnel..	34
Yield point (YP)...........lb/100 ft^2..	7
Plastic viscosity (PV).............cp..	13
YP/PV..................................	0.54
10-sec gel.................lb/100 ft^2..	0
10-min gel.................lb/100 ft^2..	9
API filtrate.......................ml..	2.5

A major factor in the successful drilling of Sportsman No. 1 was that the drilling fluid retained its properties when exposed to an estimated bottom-hole temperature of above 316° C. Flowline temperature of the fluid was maintained at 70° to 108° C with the aid of a 7-foot wooden cooling tower and an electric fan.

On O'Neill's Geothermal IID No. 2, the fluid was cooled by a large heat exchanger instead of the customary cooling tower. The heat exchanger consisted of a 2,300-foot continuous coil of 6-inch, thin-walled, steel pipe laid

in a 4-foot-wide by 4-foot-deep by 1,500-foot-long ditch, through which the hot fluid from the rig suction pit passed before being returned downhole. Water from the nearby Alamo River was pumped into the heat exchanger ditch at a rate of 600 gal/min to cool the fluid. The water then discharged into the Salton Sea, the normal discharge point of the Alamo River. In 1961, the estimated cost for drilling a 3,000-foot well was $80,000, compared with $125,000 for a 5,000-foot well. Current costs would be substantially higher.

Problems Encountered (8)

Lost-circulation zones are present anywhere from the surface to total depth. Replacement of lost-circulation material is sometimes required to regain fluid returns, although in most cases the formation collapses near the borehole and heals itself in a few hours. Lost circulation was a significant problem below 5,100 feet in the Bureau of Reclamation's Mesa 6-1 test well drilled in 1972 on the East Mesa near Holtville, Calif. At 7,419 feet, circulation was lost completely and could not be restored by introducing mica flakes, fiber, seed hulls, or other lost-circulation agents into the fluid system. Satisfactory operation was finally restored after cementing, continually adding water and lost-circulation material, and maintaining pump pressure at about 800 psi. Water loss was attributed to evaporation due to high flowline temperature and low relative humidity in the Imperial Valley.

Steamboat Springs, Nevada

Description (32)

The Steamboat Springs geothermal area is in southern Washoe County Approximately 8 miles south of Reno, Nev. The most intense thermal activity is centered in a 4-square-mile area.

There are three systems of faults in the thermal area: An east-northeast system parallel to the axis of Steamboat Hills, which is largely restricted to Lousetown lava flows and older rocks; a system of northwest-striking faults, which control Pine Basin; and a third system consisting of numerous faults striking generally north.

Drilling Fluid Technology (6, 17)

Nevada Thermal Power's Steamboat well No. 1, typical of the area, was drilled to a depth of 1,078 feet with a low-pH, lignite-surfactant fluid. This fluid was formulated to minimize fluid losses and repress cementation reactions that might occur when high bottom-hole temperatures are encountered. The drilling operators anticipated high temperatures and high-pressure steam at depths of 1,000 to 2,500 feet, but extreme temperatures were not encountered in Steamboat well No. 1. The maximum bottom-hole temperature at 1,078 feet was only 120° C. The field trial of the surfactant fluid demonstrated that the preparation and maintenance of such a fluid was relatively easy and inexpensive. Routine test data indicated that the lignite-surfactant fluid would retain reasonable filtration (thin filter cake and low fluid loss) and rheological properties when subjected to extreme temperatures.

In drilling the well through the first 375 feet of depth, a 10-lb/gal spud mud (drilling fluid used to start the well) prepared from Wyoming bentonite, barium sulfate, and water was used. The spud mud was converted to a lignite-surfactant fluid by first watering back the spud mud and adding 50 pounds of soda ash to remove calcium and magnesium cations and then adding approximately 100 pounds of salt, 920 pounds of drilling fluid surfactant, 2,250 pounds of lignite-surfactant, an additional 250 pounds of soda ash, and finally 200 pounds of caustic soda. The total conversion time was about 45 minutes. This fluid was then used to drill the well from 375 feet to total depth without further problems. Maintenance of the fluid during this period consisted of adding 800 pounds of bentonite, 8,000 pounds of barium sulfate, 100 pounds of soda ash, and 557 pounds of surfactant. The materials used for drilling fluid in Steamboat well No. 1 are shown in table 3.

TABLE 3. - Materials used in Nevada Thermal Power's Steamboat well No. 1 from 0 to 1,078 feet

Material	Amount,[1] lb
Wyoming bentonite	5,100
Barium sulfate	34,900
Salt	100
Surfactant	1,640
Lignite	2,250
Soda ash	400
Caustic soda	200
Diesel fuel	300-400

[1]Includes materials used in the spud mud.

The fluid returning to the surface was cooled through 800 feet of 2-inch line submerged in water.

The bottom-hole temperature surveys were made at various depth intervals. The fluid pumps were shut down for 3 to 5 hours, and measurements were made every 30 minutes with a maximum-recording thermometer. Table 4 lists properties of the surfactant fluid at various depths.

TABLE 4. - Properties of surfactant fluid at various depths of Steamboat well No. 1

Depth, ft	Weight, lb/gal	Plastic viscosity, cp	Yield point, $lb/100\ ft^2$	Initial gel, $lb/100\ ft^2$	10-min gel, $lb/100\ ft^2$	API filtrate, ml	Filter cake, in
393	10.3	30	8	4	9	3.6	2/32
432	10.6	28	12	2	10	4.2	2/32
462	10.7	29	10	4	9	3.6	2/32
523	10.8	30	7	4	9	3.6	2/32
603	11.1	34	6	5	9	3.6	2/32
634	11.4	36	7	4	6	3.0	2/32
873	10.7	19	3	3	6	3.6	2/32
1,030	11.4	42	12	3	7	3.6	2/32
1,077	11.1	47	12	3	17	3.8	2/32

Problems Encountered (6)

Several problems controlling the vapor pressure in a high temperature shallow-well system were readily apparent. These problems were mechanical and required methods such as surface condensing, down-hole cooling, and pressurizing the circulating system to reduce and control the vapor pressure of the drilling fluids.

A large amount of foam was prevalent in the surfactant fluid. This problem was controlled by adding 4 to 6 gallons of diesel oil to the suction pit as needed.

Hawaii

Description (26)

In November 1959, volcanic eruption produced a lava lake containing about 100 million metric tons of molten lava in the Kilauea Iki Crater. During the eruptive phases lava flowed into the crater, filling it to above the vent elevation. In the quiet periods of the eruptive cycles, lava flowed back onto the feeding conduit, and the resulting lake of molten rock was covered by a solidified crust of lava.

Field Development

The near-surface occurrence of naturally produced molten rock offered a unique opportunity for studying very hot underground energy sources. The objective of the study was to obtain knowledge of the drilling problems encountered while probing into hot and sometimes molten lava. A test well was drilled by the Lawrence Radiation Laboratory of the University of California.

A portable core-drilling rig featuring a manually controlled screwfeed enabled the operator to determine whether difficulties were developing during drilling. An air compressor located on the crater rim was used to supply air circulation. Approximately 1,400 feet of air line connected the compressor to the drill. A cable and winch were used to transport equipment to and from the crater floor.

Drilling was started with a 3-inch-diameter hole. Compressed air was used to remove the cuttings and cool the drill tools. At 8 feet, the bit was changed to 1-7/8 inches to reduce drilling vibration and increase the efficiency of the air coolant. A 1-7/8-inch-diameter hole was then drilled to the 14-foot level. The hole was cored to AX (1-5/8-inch-OD) size and then reamed to NX (2-3/8-inch-OD) size in order to accommodate installation of a 2-inch-diameter casing. AX coring bits then were used to drill from 14 feet to the final depth of 20 feet.

At about 19 feet, the crust-melt boundary was encountered, and the melt became quite fluid at 20 feet. At 19.5 feet, the tools slowly dropped into the hole under their own weight. At 20.4 feet, further removal of the melt did not deepen the hole because of the decreased viscosity of the melt.

Drilling Fluid Technology (26)

Air was selected as the coolant medium to determine the feasibility of its use where temperatures exceeded 800° C, and to avoid water contamination of gas samples which were obtained upon reaching the melt. Drilling with air progressed satisfactorily to a depth of 12 feet (850° C) and with some difficulty to 16.8 feet (1,025° C). At that depth, due to slow drilling progress and excessive damage to the bits, water was used to cool the hole. (It should be noted that the bits being used were not specifically designed for air drilling, that the air circulation was not optimum because the compressor was located 1,400 feet from the drill rig, and that the fresh basalt rock was extremely hard--about 6 on Mohs' scale--and not friable.) With the drill tools out of the hole, approximately 5 gallons of water were slowly poured into the hole to cool the rock. The tools were then lowered for drilling, and water was periodically injected into the compressed-air line. After drilling 6 or 8 inches the cycle was repeated. This air-water vapor coolant worked quite well, and the drilling rate increased from 0.2 ft/hr to 1 ft/hr. Core recovery was poor, but there was little damage to the drill bit.

Problems Encountered (26)

The major drilling problems encountered were excessive chipping and rapid wearing of the Kennametal[5] and Carboloy teeth and shattering of diamond teeth on the drill bits. Chipping was partly due to the vibration of the small drilling rig when air circulation was used for cooling. It was evident that much of the damage was due to inadequate heat removal by the circulating air. When water was used to cool the drill string and the hole bit, wear greatly decreased and the drilling rate significantly increased. Circulation ports occasionally clogged with core and rock chips; then, from lack of cooling, the diamond teeth would shatter and the silver solder weld on the Kennametal would melt.

Progress was also hindered at a depth of 15 feet because threads on the core barrel and drill bits "locked" owing to thermal expansion of the metal. This problem was eliminated by using powered graphite to lubricate the threads.

FOREIGN GEOTHERMAL ENERGY AREAS

Italy

Description (10, 12)

Nine thermal fields lie in a 310-mile zone on the western side of the Appennine Range in central Italy. The Larderello thermal region, the most important and productive of the thermal fields, is at the northwestern end of the zone, approximately 125 miles northwest of Rome.

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[5]Reference to brand or trade names is for identification only, and endorsement by the Bureau of Mines is not implied.

The cap rock of the Larderello area consists of clay shales, marl, siliceous limestones, and sandstones. This impervious formation covers the underlying permeable structures, which are fractured limestones and anhydrites (Middle-Lower Triassic). These must be regarded as the most interesting formations because of their permeability.

Below the limestones and anhydrites are Lower Triassic and Permian formations, which are also often productive. They consist of anagenitic quartzites, gray-green clay schists, and greenish metamorphic, often sericitic clay schists. The geothermal gradient of the Larderello area is abnormally high, being approximately 8° C per 100 feet. The Agnano No. 1 well was drilled in Naples Province, 15 miles west of the crater of Mt. Vesuvius, in rocks of volcanic origin with bottom-hole temperatures of about 300° C.

Field Development (3-4, 21)

The depth of the wells in the Larderello region, depending on the thickness of the impermeable cap rock, ranges from approximately 1,000 feet to approximately 5,200 feet.

Since the upper portion of the formation is heterogeneous in character, deviation from the vertical must be guarded against. In an attempt to improve drilling, a smaller drill has been used during the initial drilling period. This affords a high ratio between the diameter of the drill collar and the diameter of the hole. The widening of this guide hole is performed by appropriate reamers formed by a series of milling cutters similar to those of rock bits. The calcareous formations consisting of shaley clays, dolomitic limestones, and quartzites are so hard and require such intense abrasive action that drills with conical cutters and teeth made of a highly resistant material have to be used.

In the deeper wells, after cementing a 17-1/4-inch surface casing, a 13-3/8-inch casing is run from the cap rock formation to the top of the producing formation. The 13-3/8-inch casing is cemented to within approximately 100 feet of the end of the last casing after which drilling continues and a 12-inch casing is set through to the production zone. Immediately after the installation of the last casing, a special device to prevent sudden blowouts is installed at the wellhead.

At present, geothermal well drilling in the Larderello region remains very similar to that of oil drilling, except for minor adjustments. Geothermal wells require larger diameter pipe for production. This means, for the same depth, rigs used in geothermal drilling must withstand higher loads. Also in geothermal wellhead equipment, the following special conditions must be considered: (1) High fluid deliveries, (2) low well closing and operation pressures, (3) high temperature of both the mud and the steam, (4) strong corrosive action of the fluid delivered (particularly during blowout), and (5) connection to large-diameter pipelines.

The deepest well in the newly opened field in the Naples Province was the Agnano No. 1, with a total depth of 6,044 feet. Surface casing consists of 18-5/8-inch conductor pipe, followed by 9-5/8-inch pipe with a 6-5/8-inch production pipe set to a depth of 5,673 feet. All strata penetrated consisted of volcanic products with calcium carbonate and epigenetic pyrites in diffuse form. Owing to the nature of these formations, the continuous use of rock bits during the drilling was necessary.

Drilling Fluid Technology (5, 10, 21)

The Agnano No. 1 well was drilled with a tannin-thinned fluid. Tables 5, 6, and 7 give the principal properties of the base fluid used at Agnano No. 1, aged for various time periods. The figures in tables 6 and 7 for specially treated fluids can be compared with the base fluid properties given in table 5. The effect of the correctives was small at 20° C but very large at 85° C. The use of this fluid was restricted to operating conditions where the fluid temperature did not exceed 120° C.

TABLE 5. - Principal characteristics of a bentonite-based fluid used at Agnano No. 1, Naples, Italy

Characteristic	At 20° C	After 4 hr at 66° C	After 8 hr at 85° C
Weight..............................lb/gal..	8.8	8.8	8.8
Viscosity.............................min..	12	22	54
Filtrate...............................ml..	8	11	25
Filter cake............................in..	2/32	2/32	8/32
pH..	9.5	8.5	8.5

TABLE 6. - Principal characteristics of a bentonite-based fluid plus 0.7 lb/bbl quebracho and 1.4 lb/bbl sodium carbonate used at Agnano No. 1

Characteristic	At 20° C	After 4 hr at 66° C	After 8 hr at 85° C
Weight..............................lb/gal..	8.8	8.8	8.8
Viscosity.............................min..	11	13	24
Filtrate...............................ml..	8.5	10	13.5
Filter cake............................in..	2/32	2/32	3/32
pH..	11.5	11	11

TABLE 7. - Principal characteristics of a bentonite-based fluid plus 1.4 lb/bbl quebracho and 2.8 lb/bbl sodium carbonate used at Agnano No. 1

Characteristic	At 20° C	After 4 hr at 66° C	After 8 hr at 85° C
Weight..............................lb/gal..	8.8	8.8	8.8
Viscosity.............................min..	10.5	11.5	15.0
Filtrate...............................ml..	9	9.5	11
Filter cake............................in..	2/32	2/32	2/32
pH..	12/5	12	12

Field experience in the Larderello region, as well as laboratory tests, have shown that thermal degradation of solid components was increased by exposing the drilling fluid to high temperatures. The harmful effects of high temperatures--that is, flocculation or gelling effect of the clay--could be clearly observed in fluids that were aged for several hours at 100° C.

To avoid gelling and high filtration losses, which can occur even at lower temperatures, certain additives were used to control these properties. The fluid system was conditioned with carbonates, carboxymethylcellulose (CMC), and tannins in caustic soda, keeping the fluid at pH 8. CMC was used to control the liquid phase of the fluid by reducing the filtrate loss to the formation. It also improved the distribution of the solids and maintained their concentration at appropriate values by effectively increasing the viscosity of the fluid. Tannins were used to make the fluid more mobile.

At the Larderello region, when higher temperatures (>120° C) were encountered, fluids pretreated with ferrochrome-lignosulfonate and chromelignins were used. These materials acted as thinners and filtrate control agents as well as resisting the degrading action of high temperatures. Since these products are organic acids at room temperature, they were always used with sodium hydroxide in order to maintain the fluid pH at 8 to 9. Deterioration of the fluid was noted above 170° C and resulted in the flocculation of the clay solids. This flocculation was reduced by the addition of sodium chromate (0.1 percent). Table 8 compares the properties of the three types of fluid used in the Larderello region.

TABLE 8. - Typical properties of fluids used in geothermal drilling in the Larderello, Italy, area

Mud property	Conventional mud	Conventional mud with CMC and tannin added	Ferrochrome-lignosulfonate and chromelignin mud
Weight........................lb/gal..	11.0	11.1	11.1
Plastic viscosity................cp..	20	16	10
Yield point..............lb/100 ft^2..	30	18	12
Initial gel strength.....lb/100 ft^2..	0	0	0
10-min gel strength......lb/100 ft^2..	20	16	10
API filtrate.....................ml..	19	17	15
Filter cake......................in..	2/32	2/32	1/32
pH................................	8	8	9

The adoption of air drilling for small-diameter boreholes in the Larderello region was a development of great importance in prospecting for steam. The requisite number of holes were drilled rapidly and cheaply to ascertain the zones of maximum permeability along faults and to provide all the necessary data for the systematic exploitation of the field.

The main attractive features of compressed air drilling found at Larderello may be summarized as follows: (1) Higher drilling rate, (2) longer life of the rock bit, and (3) less possibility of contamination in the

productive zones and constant check on geothermal manifestations. A limiting factor in the use of air drilling was the presence of liquid in the form either of infiltrating water or of endogenous fluid from the covering formations. Under certain conditions, the endogenous fluid flowing into the borehole, in conjunction with the circulating air, was utilized to bring up and expel the drill cuttings. The most outstanding results and the best possible working conditions were attained when it was possible to use air in drilling completely dry ground. Statistics on steam drilling showed that when air was used in place of fluid, especially in hard formations, there was an appreciable increase in penetration rate and in the life of the rock bit. The increase in drilling rate was due to the better removal of cuttings by the high-speed air around the rock bit, the high-speed flow of air up the annulus, and the very low viscosity of the drilling air.

Problems Encountered

Drilling was often impaired or interrupted at Larderello by the absorption of drilling fluid into the formation and also by lost circulation occurring in the cap rock. Circulation was easily restored by adding sealing materials to the fluid. These were usually of vegetable origin; however, mica and cellophane were used also. As a rule, when circulation was completely lost, four kinds of sealing slurries were used to alleviate this problem. The materials and techniques used are as follows:

1. Cement slurry. Cement was mixed with water to a weight of 15.8 to 16.3 lb/gal. This mixture, besides being very dense, was also quite viscous and had a reduced setting time.

2. Gel-cement. A gel-cement was prepared by adding the proper quantity of cement to water containing 6 percent prehydrated bentonite and 6 percent perlite; percentages refer to the weight of cement used. The slurry thus formed had a lower density, higher gel strength, and higher set strength than one formed by adding water to the dry mixture. As a general rule, the use of gel-cement was indicated when dealing with fractures characteristic of calcareous formations.

3. Natural clay. Since drilling was performed with bits of rather large diameter, it was possible to attempt sealing procedures with natural clay, which was usually available onsite. Once the depth of the fracture was determined, clay in large pieces or shaped into balls was thrown into the well. When the efficiency of the seal was ascertained, normal drilling was carefully restored.

4. Diesel oil-bentonite-emulsifier slurry. This slurry was prepared from diesel oil, bentonite, materials to block large pores and thus prevent lost circulation, and an emulsifier. The materials were mixed at the surface and pumped into the well through the pipe string after eliminating water or drilling fluid by means of a diesel oil cushion. Although this slurry produced good results when used in induced fractures, it was used in only the most difficult cases because it was difficult to obtain proper mixing.

New Zealand

Description (15)

The geothermal fields of New Zealand lie in the Taupo volcanic zone, a 9- to 15-mile-wide belt in the center of North Island that extends for over 185 miles in a northeasterly direction. Fumeroles and hot springs are numerous in this particular geothermal area. The reservoir rock, the Waiora Formation, is a permeable pumice breccia, 1,600 to 3,300 feet thick. It is covered by 230 to 550 feet of a relatively impermeable cap rock, the Huka Falls Formation, composed of siltstones, pumiceous sandstones, and diatomites. Below the pumice breccia is found the Wairakei Formation, a relatively impermeable sequence of dense ignimbrite sheets, at least 2,000 feet thick. Indirect evidence points to the presence of a sedimentary graywacke basement 13,000 feet below the surface. The steam is channeled into the reservoir by several major faults.

The Wairakei field is of Middle Pleistocene age. Magmatic origin has been proposed for the steam. Ground temperatures can be as high as 250° C at depths of 2,000 feet.

Field Development (30)

Drilling for geothermal steam commenced at Wairakei in 1950 with light rotary rigs, drilling 4-inch exploration holes to depths of 1,500 feet.

Drilling in the Wairakei field virtually ceased in 1964. Apart from two further bores drilled in 1965 and further production drilling at Kawerau in 1967, all drilling has since been carried out for the investigation of possible production fields at Tauhara, Orakeikorako, Rotokawa, and Broadlands. Improvement of techniques, wellheads, casing joints, and mud properties has resulted in an excellent record of safe and successful drilling.

Drilling Fluid Technology (2, 11, 13, 28, 30, 33)

Experience at Wairakei prior to 1958 indicated that a fluid of the composition shown in table 9 was satisfactory. More bentonite and additives such as lignin compound and sodium carboxymethylcellulose were added as required. A fluid density of 69 to 73 lb/ft^3 was generally found to be satisfactory.

TABLE 9. - Materials used at Wairakei, New Zealand, prior to 1958

Material	Amount, lb
Clay	1,780
Bentonite	500
Caustic soda	4.2
Water	7,500

Circulation rates varied between 250 and 350 gal/min while drilling. The fluid was cooled by bypassing a portion of the returns to a cooling tower.

Returning fluid temperature was usually 55° to 65° C, and cooling reduced this temperature by 20° C. When circulation was stopped, temperatures approaching the fluid boiling point were often reached. Between 4 and 6 million Btu/hr was normally extracted from the bore by the drilling fluid. Barite was used as weighting agent when required to prevent contamination of the drilling fluid with in-flowing formation water. On rare occasions, densities as high as 81 lb/ft^3 were required.

However, it was found that well control was easier by cooling the fluid rather than using weighting addition. Drilling was usually begun with a 45-second viscosity (Marsh funnel) but was lowered to about 32 seconds after the anchor casing was placed. No additives were used in the drilling fluid to prevent flocculation, but care was taken to assure that no cement or cement grout was allowed in the main fluid supply since such contaminants were found to cause immediate flocculation.

On the return from the bore, the fluid was first cleaned from the drill cuttings by being passed through vibrating desanding screens. On the larger rigs, the fluid was then allowed to pass through timber settling tanks to remove smaller sand particles. The fluid was then passed through cooling tanks where it was agitated and kept moving in long channels, or elevated to a cooling tower and dropped through a series of baffles to give maximum contact with the air. Native clays and bentonites were found to be so subject to high-temperature gelation that it was very difficult to restore circulation if circulation was halted for more than one-half hour.

Woods (33) reports that in 1961 some wells at Wairakei were drilled using fluids containing up to 10 volume-percent diesel oil with CMC which was added directly to the fluid tanks and gunned until it was thoroughly mixed into an emulsion. Usually water was added at a slow rate to the fluid in the return flow line to make up for filtrate lost to the formation being drilled. The range of fluid properties for these wells is shown in table 10.

TABLE 10. - Range of drilling fluid properties normally used at Wairakei, New Zealand

Density....................................lb/ft^3..	69-73
Viscosity (API funnel)............................sec..	30-50
Initial gel strength (Stormer).......................g..	0-5
10-min gel strength (Stormer)........................g..	0-20
Filter loss (API 30 min).........................cu cm..	2-6
Filter cake (API 30 min)............................in..	1/32-2/32
pH..	10-12
Oil...pct..	10
Sand content..pct..	0.5-2.5

Fluid temperature, density, funnel viscosity, water loss, filter cake thickness, sand content, and pH were checked hourly while drilling was in progress. Tests on gel strength were run daily, as were retort tests for oil, water, and solids percent. Periodic monitoring of calcium and chlorides was performed also. Excessive cement (calcium) contamination was treated with

sodium bicarbonate, while tannin chloride contamination was treated with caustic soda or tannin.

In wells drilled in the late 1960's at Broadlands, tannin was largely used as a fluid thinner down to 1,000 feet and in relatively cold bores. After shutdowns and in hot conditions, the tannin-treated fluid returns became extremely thick, almost solid in nature. As a result the fluid had to be discarded and circulation broken at frequent intervals.

When drilling below 1,000 feet and under hot conditions, a chrome lignosulfonate-lignite thinner was used with beneficial effects both in the ease of resuming circulation after coring trips and in circulating good, usable fluid out of the hole after periods of shutdown. Table 11 gives an analysis of the fluid materials used for the bores at Broadlands.

TABLE 11. - Materials used for drilling fluids at Broadlands, New Zealand

Well	Total depth, ft	Bentonite, tons	Caustic soda, tons	CMC, tons	Tannin, tons	Lignosulfonate, tons	Lignite, tons	Sodium bicarbonate, tons	Diesel oil, gal
BR 2	3,392	107.1	1.3	0.7	0.5	3.3	1.7	-	5,125
BR 3	2,992	209.1	2.0	1.4	3.1	-	-	0.1	9,435
BR 4	3,344	143.4	1.3	1.2	1.9	.6	.3	.2	1,550
BR 10	3,566	61.9	.6	.2	.6	.7	.3	-	1,315
BR 12	4,492	33.5	.6	.3	-	1.3	.6	.1	-
BR 15	7,933	829.3	8.75	4.6	-	12.4	6.2	6.4	22,250

Total fluid storage in surface tanks was 32,000 gallons. Return flow from the bore passed over a single shale shaker with a 40-mesh screen and was then pumped through a battery of four centrifuges to remove sand. After passing the shale shaker, the fluid was pumped over a cooling tower at a rate of approximately 800 gal/min. The cooling tower was equipped with a 9-1/2-hp electrically driven forced-draft exhaust fan. Top and bottom guns on all tanks were used to provide continual agitation of the fluid.

Fluid properties were continually maintained and tested for production or investigation drilling. Table 12 lists the values to which the fluid properties were normally held.

TABLE 12. - Normal values of fluid properties at Broadlands, New Zealand

Weight........................lb/gal..	9.1-9.4
Funnel viscosity (Marsh)..........sec..	40-50
10-min gel strength........lb/100 ft^2..	7-15
Filtrate.......................cu cm..	5
Filter cake......................in..	1/32
pH................................	9-10

Problems Encountered (30)

Loss of circulation continued to be one of the major problems associated with the successful drilling and casing of bores down to the productive level at Broadlands. Normal practice was to pump slugs of high-gel fluid as a first resort and to apply a squeeze at the wellhead to force this gel into the formation. Cellophane flakes and sawdust were often added. Cottonseed hulls and proprietary brands were used but showed no real advantage over the considerably cheaper products. On occasion, a diesel-bentonite slurry was pumped down the drill pipe to react with water in the formation or in the fluid at the point of lost circulation. This reaction, which forms a stiff bentonitic putty, was found to be reasonably successful.

When the above methods failed, 300- to 400-gallon batches of cement grout (14.7-lb/gal) were pumped into the "thief" formation and allowed to stand for 6 hours before drilling continued.

The fluids used were found to suffer from the usual high-temperature effects, high water loss and high gel strengths. However, few problems have been experienced due to the comparatively shallow areas of the bores and the drilling practice used.

Japan

Description (15)

The geothermal areas of Japan are located in volcanic regions of Miocene and Pliocene age composed mainly of dacitic and andesitic lavas and welded tufts. Hydrothermal alteration is very pronounced both on the surface and at depth. Steam production originates primarily from well-developed cracks in hard-welded tufts.

Field Development (24)

Rotary drilling in volcanic territory usually encounters numerous problems before the ultimate depth is reached. Despite comparatively shallow depths, drilling techniques under these conditions of very hard formations and high temperatures are quite similar to those employed when exploring below 10,000 feet in an oil well. Modern drill bits, especially designed for hard formations, are used.

Drilling Fluid Technology (20, 23-24)

Early wells were drilled using bentonite-water or oil-emulsion fluids. The primary advantage of an oil-emulsion fluid was the reduction in torque on the drill string. Actual records from a well drilled by the Shunam Drilling Co. of Tokyo prior to 1961 show that after converting the conventional bentonite fluid to an oil emulsion, the torque was reduced by 40 percent.

Although most drilling fluids were adversely affected by high temperatures, a high-pH, oil-lime emulsion fluid exhibited less change than the

others. This stability made the oil-emulsion fluid more suitable for drilling in these high-temperature and high-pressure areas.

In many cases, the filtrate loss to the formation of the oil-emulsion fluid was adjusted to 1.0 ml or less and maintained during the full drilling period. This property proved to be most effective during the drilling-in period, in preventing filtrate invasion of the productive zone, and in drilling through heaving, sloughing, and caving formations.

A stable emulsion was prepared by mixing oil, water, and an emulsifying agent. All the solids of colloidal size in a clay-water fluid can serve as emulsifying agents. These include bentonite, quartz, barite, and organic particles such as starch, carboxymethylcellulose, and organic dispersants. The reaction of an emulsion fluid to dilution, temperature, and contamination by salt, anhydrite, and cement is the same as that of the base fluid. The treatment to counteract such effects is the same as that required by the base fluid. Organic thinners, lignites, lignosulfonates, and quebracho were used as dispersants and emulsifying agents.

The literature indicates that neochromite fluids consisting of a 3:1 mixture of ferrochrome lignosulfonate and chromite were used successfully in a well drilled after 1971. The chromite was treated with a bichromate to reduce viscosity and gel resistance. The chromite had a pH of about 9 and was a chelated lignosulfonic and huminic acid.

Matsuo (20) describes a later drilling program in which drilling was carried out using clay-based fluids below 150° C. Above this temperature, problems with excessive gelling and increases in amount of filtration were encountered.

Chrome-lignite and chrome-lignosulfonate fluids were used at higher temperatures, and where cement contamination was pronounced. The composition given in table 13 was stable up to 250° C and had the characteristics shown in table 14. Natural draft and forced draft cooling towers were used which lowered fluid temperatures by 14° and 22° C.

TABLE 13. - Composition of typical stable drilling fluid used in Japan

Materials	Wt-pct
Bentonite	8 -9
Blended lignosulfonate compounds	4 -5
Sodium hydroxide	.1 - .15
Defoamer	.02- .05

TABLE 14. - Properties of typical stable drilling fluid used in Japan

	150° C	200° C
Heating time..hr	16	16
Apparent viscosity..cp	12	15
Plastic viscosity..cp	10	13
Yield point..lb/100 ft^2	4	4
Gel strength..lb/100 ft^2	1-10	1-16
Water loss..ml	9.0	10.2
pH value	10.5	10.5

Iceland

Description (12)

Geologic and seismic refraction studies indicate that Iceland is built up of typically inhomogeneous layers of Tertiary basalt reaching thicknesses of 2 miles or more. These layers are overlain by Quaternary basalts mainly in the central and southern parts of the island. The mid-Atlantic Ridge passes through Iceland and causes measurable modern rifting, recent volcanism, and a noticeably high heat flow. The Tertiary volcanic districts have minor recent faulting and hot water areas with temperatures below 150° C. The Quaternary districts occur along a major through-going northeast-southwest rift zone that bifurcates to the southwest. This rift contains spring areas with subsurface temperatures from 110° to 205° C and large areas of hot ground, natural steam vents, and thermal metamorphism.

Individual surface thermal areas are controlled by intersections of contacts between permeable volcanic layers, dikes, and faults. Several thermo-artesian circulation systems are believed to come from close contact with magmatic intrusions, the ultimate heat sources for the high-temperature areas.

Thermal fields in Iceland may be divided into two groups: (1) Natural steam areas with a base temperature above 150° C, and (2) hot water areas where the base temperature is not much higher than 100° C.

Of the four thermal areas where drilling has been performed, two areas belong to each of the above-mentioned groups. The natural steam areas are Hveragerdi and Krysuvik. In these areas boiling temperatures reach practically to the surface, and blowing steam may be encountered at 164 feet or less.

Field Development (16)

Drilling for natural hot water was started in Iceland in 1928. After World War II, modern drilling tools were used with good results for drilling both hot water and natural steam. Since the hot water wells and steam wells produce flow under their own pressure, these wells were lined with casing down to a considerable depth so that the rate of flow and pressure could be regulated according to demand.

Great care must be taken when preparing a foundation for drilling equipment during freezing weather. If the ground is frozen when drilling is started, the hot drilling fluid being circulated in the well can thaw the ground, which causes shifting of the foundation and subsequent tilting of the drill rig. To have full control of these wells while drilling, a blowout preventer is placed on a string of intermediate casing set to a depth of 100 to 130 feet.

The formations drilled were mostly basalt, and although highly altered by thermal action, have proved to be substantial enough to allow the well to be completed without casing. Tricone roller drill bits designed for medium-hard

formations were most commonly used. The average life of the bits was 40 to 50 hours, and each bit drilled from 325 to 1,300 feet at a penetration rate of 3 to 65 feet per hour.

Drilling Fluid Technology (16)

Anhydrate and gypsum contamination or salt contamination of the drilling fluid did not present any problems. Control of the fluid loss was not important. The only functions required of the drilling fluid were to lift the cuttings out of the well and to cool and lubricate the bit and drill string. This was done by a mixture of bentonite and water with an occasional addition of barium sulfate in order to raise the weight of the fluid to prevent blowout. However, in most cases, cold water pumped down into the well was just as efficient in keeping the well under control, besides being cheaper than a barium sulfate fluid. Contamination from cement caused flocculation of the bentonite-water mixture and was treated by adding reacted caustic-tannin to the fluid. Small lost-circulation zones were plugged by adding a blend of cane and wood fibers. Larger lost-circulation zones, where most or all of the fluid was lost, usually meant that drilling had to be discontinued since these zones were in the hot-water-carrying zones. If further drilling was required for temperature surveys or other reasons, these zones were plugged by pumping cement through the drill pipe and squeezing it into the formation.

While drilling, the temperature of the fluid returning from the hole was continuously checked. If the temperature rose above 85° to 90° C, drilling was stopped and cold water was added to the fluid and circulated in the well until it was cooled to about 60° C or less. When the drilling was finished, the well was cleaned of all drilling fluid as far as possible by circulating water through the drill pipe for a few hours. The drill string was then removed from the well.

The fluid program accounted for approximately 5 percent of the total cost of drilling the wells in both the Hveragerdi and Krysurik areas.

Turkey

Description (9)

The first geothermal well drilling for natural steam at Kizilderi, Turkey, was started in 1968. The thickness of the cap rock changes from place to place in the area. From the surface down to the reservoir, the cap rock is composed of a layer of marl overlaying a layer of siltstone. The reservoir itself is fractured limestone.

Field Development (9)

Up to 1970, seven test wells had been completed. Drilling operations were carried out under the supervision of a drilling expert from the United Nations. Both gradient and test wells were opened. The gradient wells were only about 300 feet deep, whereas the test wells penetrated the steam reservoir at 2,100 feet. Wells were started with a 17-1/2-inch-diameter

hole. For the first 30 to 40 feet, a 13-3/8-inch surface casing was set and cemented up to the surface. Then a 9-5/8-inch casing was set down to the reservoir. The reservoir was drilled with a 8-1/2-inch diameter bit, but no casing was set. Wells were normally drilled to a depth of about 2,000 feet.

Drilling Fluid Technology (9)

Wells were drilled down to the reservoir with water-based bentonite and quarry clay fluids. Cold water was added to prevent thermal alteration of the fluid at high temperature. A chrome lignosulfonate was used as a thinning agent.

In the reservoir the circulation was lost, and the drilling was continued with water without circulation with the cuttings thrown into reservoir cracks.

SUMMARY

Geothermal well drilling differs from oil well drilling in that the formation pressure in a geothermal well is less than in a petroleum well even though the temperatures encountered are usually much higher in geothermal wells. Geothermal formations are usually more highly fractured than oil-bearing formations, which makes lost circulation of the fluids more of a problem.

Water-base drilling fluids of 9- to 10-lb/gal weights are relied on primarily for geothermal well use, although air drilling is sometimes used. Oil-in-water emulsion has been used in at least one location. Bentonite-lignite-water systems have been used most often, and additives such as polyacrylates, lignosulfonates, and chromates are employed to improve the properties of the basic system. Formation temperatures can reach 370° C, but the drilling fluid temperature is kept below 120° C by external cooling at the wellhead.

Drilling fluid failures are caused by exposure to extreme temperatures and/or the electrolyte encountered and is characterized by flocculation and severe gelation. If precautions are not taken, clay-base fluid can damage a geothermal formation by reducing its permeability.

Future development work is indicated on extending water-base drilling fluid temperature stability and on improving resistance to contaminants. High-temperature foam systems should also be considered.

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